Leptogenesis, or why do we exist?

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Outline

- Introduction: two problems
- Baryon and lepton number violation in the SM
- One solution: Leptogenesis (in type I seesaw)
- Constraints on neutrino parameters
- Conclusions

Please interrupt and ask plenty of questions!

Introduction

Problem #1: The universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

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Possible explanations:

- **Symmetric cosmology:** nucleons and anti-nucleons annihilate until $T \sim 20\,\mathrm{MeV} \Rightarrow$ residual nucleon to photon ratio $\sim 10^{-18}$
- η_B **as initial condition:** not compatible with inflation
- **Matter and antimatter got separated:** at $T \sim 20\,\mathrm{MeV}$ causally connected region contained $\sim 10^{-5} M_\odot$

Introduction

Problem #1: The universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

must have been generated during evolution of universe!

Necessary ingredients (Sakharov, 1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

Sakharov's third condition

System in thermal equilibrium described by density operator

$$\rho = \mathrm{e}^{-H/T}, \qquad \text{where } H: \text{ Hamiltonian}$$

time evolution of baryon number B:

$$\begin{aligned} B(t) &= \mathrm{e}^{iHt}\, B(0)\, \mathrm{e}^{-iHt} \\ \Rightarrow \langle B(t)\rangle_T &= \mathrm{Tr}\left(\mathrm{e}^{-H/T}\, \mathrm{e}^{iHt}\, B(0)\, \mathrm{e}^{-iHt}\right) \\ &= \mathrm{Tr}\left(\mathrm{e}^{-iHt}\, \mathrm{e}^{-H/T}\, \mathrm{e}^{iHt}\, B(0)\right) \\ &= \langle B(0)\rangle_T \end{aligned}$$

Baryon number is constant in thermal equilibrium

Sakharov's third condition

Baryon number B is odd under C, even under P and T
$\Rightarrow B$ is odd under $CPT \equiv \theta$

Thermal average of baryon number:

$$\begin{aligned}
\langle B \rangle_T &= \mathrm{Tr}\left(\mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\theta^{-1}\theta\, \mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\mathrm{e}^{-H/T} \theta B \theta^{-1}\right) \\
&= -\langle B \rangle_T
\end{aligned}$$

No baryon asymmetry can be generated in thermal equilibrium!

Neutrino masses

- direct mass searches: $m_\nu \lesssim 2\,\text{eV}$
- Neutrino oscillations:

  atmospheric ν oscillations: $\Rightarrow m_{\nu_i} \gtrsim 0.05\,\text{eV}$

  solar ν oscillations: $\Rightarrow m_{\nu_j} \gtrsim 0.008\,\text{eV}$

Problem #2:

ν masses are $\neq 0$ but orders of magnitude smaller than any other known masses

Both problems cannot be solved in the Standard Model
$\Rightarrow$ need extended model

Standard Model:

- left- and right-handed quarks and charged leptons
- neutrinos only left-handed. Why?

Introduce right-handed neutrinos N

First prediction: neutrino masses (type I seesaw)

$$m_\nu \sim \frac{v^2}{M}$$

$v \sim 100\,$GeV: SM mass scale; M: mass of N.
Observed light neutrino masses yield clues on M

$$m_\nu \gtrsim 0.05\,\mathrm{eV} \quad \Rightarrow \quad M \lesssim 10^{14}\,\mathrm{GeV}$$

Second prediction: lepton number L is violated
Why do we care?

Baryon and lepton number violation in the SM

Baryon (B) and lepton (L) number

$$\text{quarks:}\quad B=\frac{1}{3}\,,\quad L=0\,;\qquad \text{leptons:}\quad B=0\,,\quad L=1\,.$$

SM has global $U(1)_B$ and $U(1)_L$ symmetries:

$$\begin{array}{ll} U(1)_B: & q(x)\to \mathrm{e}^{i\alpha}q(x)\,,\quad l(x)\to l(x) \\ U(1)_L: & q(x)\to q(x)\,,\quad l(x)\to \mathrm{e}^{i\phi}l(x) \end{array}$$

$\Rightarrow$ classically conserved currents (Noether theorem)

$$\begin{aligned} \partial^\mu J^B_\mu &= \partial^\mu \sum_q \frac{1}{3}\bar{q}\gamma_\mu q = 0 \\ \partial^\mu J^L_\mu &= \partial^\mu \sum_l \bar{l}\gamma_\mu l = 0 \end{aligned}$$

decompose into chiral parts: $\bar{f}\gamma_\mu f = \bar{f}_L\gamma_\mu f_L + \bar{f}_R\gamma_\mu f_R$

The triangle anomaly

Chiral currents are not conserved at the quantum level:

$$\begin{aligned} \partial^\mu \bar{f}_L \gamma_\mu f_L &= -c_L \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} \\ \partial^\mu \bar{f}_R \gamma_\mu f_R &= +c_R \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} \end{aligned}$$

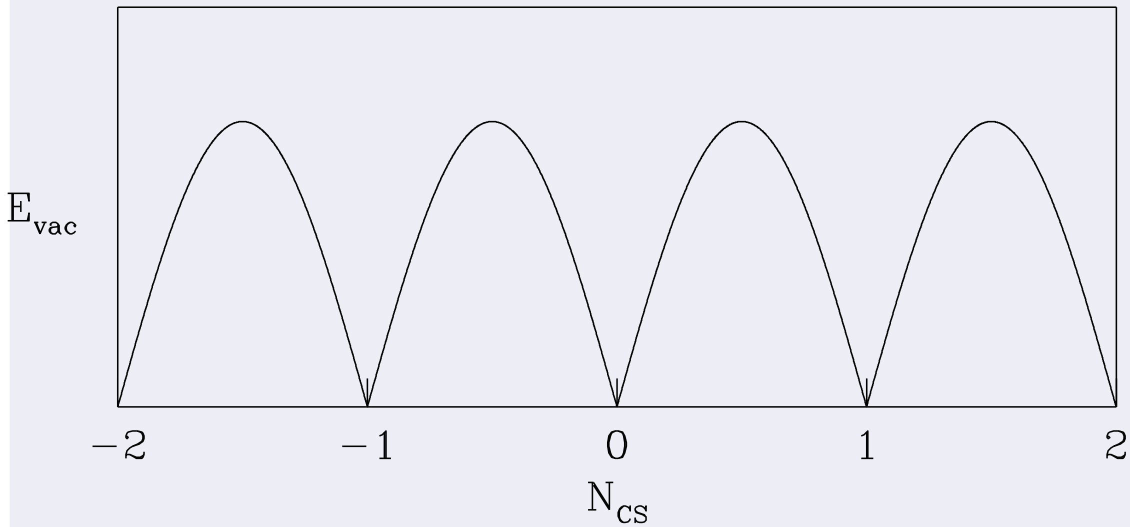
f_L and f_R have identical QCD couplings
$\Rightarrow$ no QCD anomaly in J^B_μ and J^L_μ

Left- and right-handed fields couple differently to $SU(2)_L$ and $U(1)_Y \Rightarrow$ electroweak quantum effects violate baryon and lepton number conservation:

$$\partial^\mu \left(J^B_\mu + J^L_\mu\right) \neq 0\,, \qquad \partial^\mu \left(J^B_\mu - J^L_\mu\right) = 0$$

$B+L$ is violated in SM, while $B-L$ is conserved

Vacuum structure of non-Abelian gauge theories:



Topological charge:

('t Hooft '76)

$$\Delta B = \Delta L = n_f \Delta N_{CS}$$

Transition rate:

$$T = 0: \qquad e^{-4\pi/\alpha_w} \sim 10^{-170}$$

$$T > 0: \qquad e^{-E_{sph}/T} \quad \text{with} \quad E_{sph} \sim \frac{8\pi v(T)}{g}$$

$$T > T_{ew}: \qquad \alpha_w^5 T^4$$ (Bödeker '98)

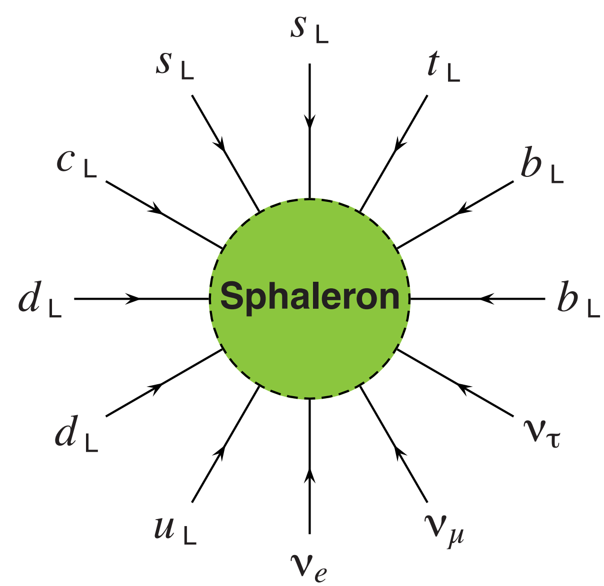
SM: $B+L$ is violated by instantons

(Klinkhammer & Manton '84; Kuzmin et al. '85)

Sphalerons are in thermal equilibrium above electroweak 'phase transition':

$$T_{ew} \sim 100 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$$

$B+L$ violated, $B-L$ conserved.



B and L are not independent at $T \gtrsim 100\,\text{GeV}$

$$\eta_B = c\,\eta_{B-L} = \frac{c}{c-1}\eta_L\,, \quad \text{with} \quad c \sim \frac{1}{3}$$

L violating processes can generate η_B!

Leptogenesis

A free lunch: Leptogenesis in type I seesaw

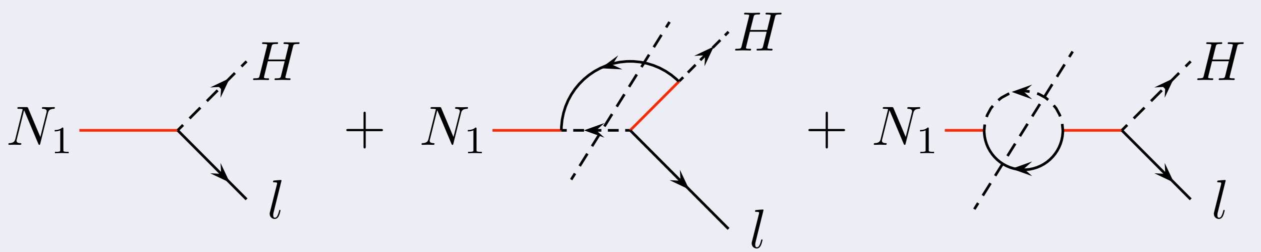
Right-handed neutrinos can also give rise to η_B (Fukugita and Yanagida '86)
Yukawa couplings:

$$\mathscr{L}_Y \simeq \overline{N}\lambda_\nu l H - \overline{N} M N$$

- Ns are unstable, decay to lepton-Higgs pairs:

$$\Gamma_D \propto \widetilde{m}_1 = \frac{v^2}{M_1}(\lambda_\nu^\dagger \lambda_\nu)_{11}$$

- N interactions violate $L \to L \neq 0$, partially converted to $B \neq 0$ by sphalerons
- λ_ν complex $\Rightarrow$ CP violation ε_i



How does a violation of CP arise?

Consider a simple example, e.g. the decay of a particle X into some final state f and the CP conjugated process $\bar{X} \to \bar{f}$

Generic amplitude at tree level and one-loop:

$$A(X \to f) = g_0 A_0 + g_1 A_1$$

Decay width at LO (tree level) and NLO (interference between tree level and one-loop):

$$\Gamma(X \to f) = |g_0|^2 I_0 + g_0 g_1^* I_1 + g_0^* g_1 I_1^*$$

$g_{0,1}$: (products of) coupling constant(s) at tree level and 1-loop
$I_{0,1}$: kinematical factors at LO and NLO (phase space, etc.)
$\to$ identical for particles and anti-particles (CPT)

CP conjugated process:

$$\Gamma(\bar{X} \to \bar{f}) = |g_0|^2 I_0 + g_0^* g_1 I_1 + g_0 g_1^* I_1^*$$

CP asymmetry:

Diference of decay widths:

$$\begin{aligned}
\varepsilon &\propto \Gamma(X \to f) - \Gamma(\bar{X} \to \bar{f}) \\
&= g_0 g_1^* I_1 + g_0^* g_1 I_1^* - g_0^* g_1 I_1 - g_0 g_1^* I_1^* \\
&= (g_0 g_1^* - g_0^* g_1)(I_1 - I_1^*) \\
&= -4 \,\mathrm{Im}\,(g_0 g_1^*)\,\mathrm{Im}\,(I_1)
\end{aligned}$$

Two different phases are needed in order to get CP violation:

1. one phase from the couplings
2. one phase from the kinematical factors: rescattering phase, arises if particles in loop are on-shell

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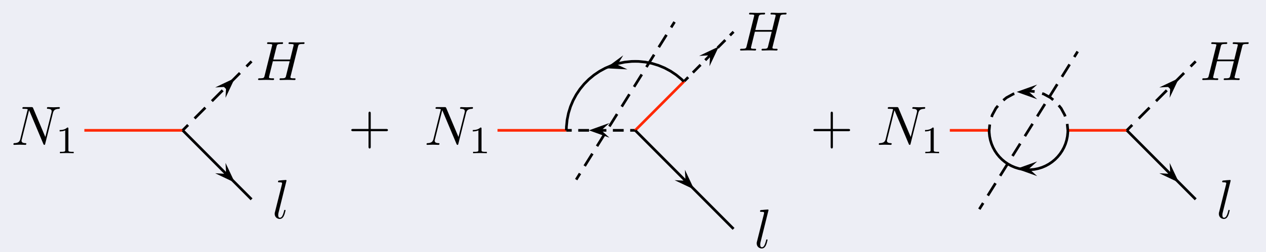
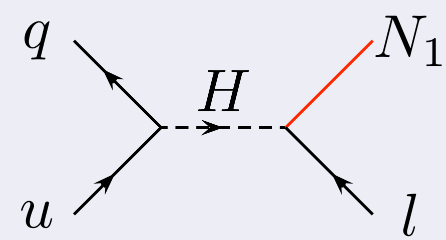


Challenge #1: How do the N get produced?

(Luty '92; M.P. '96; Pilaftsis and Underwood '03)

N scattering processes are important

all production processes $\propto \widetilde{m}_1$



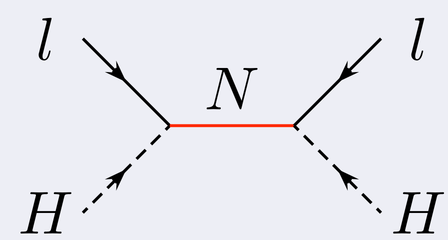
need large $\widetilde{m}_1$ for efficient production

Challenge #2: L violating scatterings can destroy η_B

(Fukugita & Yanagida '90; Buchmüller, Di Bari & M.P. '02; Giudice et al. '03)

Two contributions to reaction rate:

- resonant contribution from N_1: $\propto \widetilde{m}_1$
- remainder: $\propto M_1 \overline{m}^2$, $\overline{m}^2 = \sum m_{\nu_i}^2$



need small $\widetilde{m}_1$ and $M_1 \overline{m}^2$ to avoid washout

Two conflicting requirements

$\longrightarrow$ network of Boltzmann equations

Expansion vs. interactions:

The time evolution of number densities n is described by Boltzmann equations:

$$\frac{\mathrm{d}n}{\mathrm{d}t} + 3Hn = n\Gamma$$

Two competing terms:

1. expansion term $3Hn$ tends to drive the system out of equilibrium
2. interaction terms $\Gamma = n_{\mathrm{target}} \langle \sigma |\mathbf{v}| \rangle$ try to restore thermal equilibrium

Whether a particle species is in thermal equilibrium or not depends on ratio of scattering rate to expansion rate.

Particle falls out of equilibrium when $\Gamma \lesssim H$

Out-of-equilibrium condition:

The N_1 are not in thermal equilibrium if N decay width Γ_D smaller than expansion rate H:

$$\Gamma_D < H(T)$$

$\Rightarrow$ upper bound on effective light neutrino mass:

$$\widetilde{m}_1 \lesssim 10^{-3}\,\mathrm{eV} \quad \text{with} \quad \widetilde{m}_1 = \frac{v^2}{M_1}(\lambda_\nu^\dagger \lambda_\nu)_{11}$$

Scale of light neutrino masses

$\sqrt{\Delta m^2_{\rm sol}} \simeq 8 \times 10^{-3}\,\mathrm{eV}$ and $\sqrt{\Delta m^2_{\rm atm}} \simeq 5 \times 10^{-2}\,\mathrm{eV}$

since $m_{\nu_1} \leq \widetilde{m}_1 \rightsquigarrow$ deviations from thermal equilibrium small (?)

Rescale to get rid of expansion term:

Consider particle number N in a comoving volume element R_*^3 instead of number density n.
R_*^3 contains one photon at time t_* before leptogenesis

$$
\begin{aligned}
N(t) &= n(t)\,R_*^3(t) \\
\Rightarrow \dot{N}(t) &= \dot{n}(t)\,R_*^3(t) + 3\,n(t)\,R_*^2(t)\dot{R}_*(t) \\
\Rightarrow \frac{1}{R_*^3(t)}\dot{N}(t) &= \dot{n}(t) + 3\,H\,n(t)
\end{aligned}
$$

Replace time t by inverse temperature $z = M/T$.
In radiation dominated universe: $t = z^2/2H(M)$

$\Rightarrow$ LHS of Boltzmann eqs. can be written as:

$$\frac{H(M)}{zR_*^3}\,\frac{\mathrm{d}N}{\mathrm{d}z} = \dot{n}(t) + 3\,H\,n(t)$$

The Boltzmann equations for leptogenesis

competition between production and washout:

$$\frac{\mathrm{d}N_{N_1}}{\mathrm{d}z} = -(D+S)\,(N_{N_1} - N_{N_1}^{\mathrm{eq}})$$

$$\frac{\mathrm{d}N_{B-L}}{\mathrm{d}z} = -\varepsilon_1\,D\,(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W\,N_{B-L}$$

$z = M_1/T \quad \propto \sqrt{t}$

N_i : number densities in comoving volume

D : decays

S : $\Delta L = 1$ scatterings

W : washout due to L violating scatterings

The Boltzmann equations for leptogenesis

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produced baryon asymmetry:

$$\eta_B \simeq 10^{-2}\,\varepsilon_1\,\kappa(\widetilde{m}_1, M_1\overline{m}^2)$$

need to know:

- CP asymmetry ε_1 (from neutrino mass model)
- efficiency factor κ parametrizes N interactions (from integration of Boltzmann eqs.)

(Barbieri et al. ’00; Buchmüller, Di Bari & M.P. ’02)

Baryon asymmetry determined by four parameters

1. CP asymmetry ε_1
2. mass of decaying neutrino M_1
3. effective light neutrino mass (coupling strength of N_1)

$$\widetilde{m}_1 = \frac{v^2}{M_1} \left(\lambda_\nu^\dagger \lambda_\nu\right)_{11}$$

4. light neutrino masses

$$\overline{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2}$$

since

$$\Gamma_{\Delta L=2} \propto M_1 \overline{m}^2$$